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# Performance Evaluation of Channel Estimation Techniques for MIMO-OFDMA systems with Adaptive Sub-carrier Allocation

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**Abstract**—Dynamic Sub-Carrier Allocation (DSA) strategies have been shown previously to achieve significant performance benefits when applied to OFDMA systems and further benefits for MIMO-OFDMA systems. Analysis thus far has focussed on the assumption of ideal Channel State Information (CSI). In this paper, the impact of non-ideal CSI is investigated.

Various channel estimation techniques are evaluated for application to MIMO-OFDMA systems. They are based on Least Squares (LS) Estimation with training pilots. ‘Conventional’ (as for MIMO-OFDM) CTP (combining training pilots) and ‘improved’ (optimised for MIMO-OFDMA) STP (Separate training pilots) versions of both Frequency Domain Least Square (FDLS) and Time Domain Least Square (TDLS) channel estimation are considered, as are the options of both Space- Time Block coding (STBC) and Spatial Multiplexing (SM) as MIMO strategies. The STP-TDLS strategy is shown to significantly outperform other channel estimation options, achieving performance within 1dB of the ideal case.

Subsequently, the use of the STP-TDLS channel estimation method in conjunction with the DSA algorithm is considered in order to determine the impact of non-ideal channel knowledge on the gain achieved by DSA. The performance for the cases of ideal CSI and CSI derived via STP-TDLS channel estimation are compared and evaluated for both the STBC and SM cases. The effects of non-ideal channel estimation in both the DSA mechanism and channel equalisation separately and together are evaluated. It is shown that STP-TDLS channel estimation works better in SM (only 1dB worse than ideal CSI case) than in STBC. Furthermore, it is shown that DSA is less sensitive than channel equalisation to non-ideal CSI. The degradation of system performance in the realistic case of non-ideal CSI for both DSA and channel equalisation is a compound of the effects of the separate effects of non-ideal CSI error. It is shown here that in both STBC and SM cases, the effect is almost a linear addition of the two parts. Given the substantial benefits of DSA and its relative insensitivity to channel estimation errors, it is concluded that DSA remains a highly promising technique.

**Index Terms**— Channel Estimation, MIMO-OFDMA, TDLS, FDLS, DSA

## I. INTRODUCTION

For the support of high data rates, provision of various QoS profiles for multiple users and operation in hostile multi-path radio channel environment, OFDMA has recently been chosen for the IEEE 802.16 and DVB-RCT standards [3,4]. Further to the uplink gain achieved by concentrating uplink transmit power into a certain sub-channel, there is also the opportunity to achieve further gain by exploiting multi-user diversity – provided that a deterministic allocation of sub-carriers is employed in order to exploit the available diversity. Recently, more and more techniques for exploiting the advantages of multi-user diversity to mitigate channel fading have been proposed. Some Dynamic Sub-Carrier Allocation (DSA) algorithms have been proposed in [1,5-7] for SISO systems. The algorithm in [1] has been further extended to the MIMO case in [2] due to its low complexity and near optimum performance and is hence the DSA algorithm considered in detail in this paper. Previously, all these DSA algorithms have all been evaluated on the assumption of ideal CSI for both the DSA itself and for channel equalisation. The prime motivation of this paper is to investigate methods of channel estimation for MIMO-OFDMA and the effect of non ideal channel knowledge on the DSA algorithm.

In this paper, channel estimation methods Frequency Domain Least Squares (FDLS) [8] and Time Domain Least Squares (TDLS) [9,10] are considered for MIMO-OFDMA initially in the absence of DSA (i.e. for a pseudo-random sub-carrier allocation). The Least Squares channel estimation is derived from repeated training pilots which are equi-powered, equi-spaced and phase shift orthogonal [9]. [10,11] propose suitable orthogonal training symbols and methods for combining them at the receiver for STBC MIMO-OFDM. This method is referred to here as Combining Training Pilots (CTP). It is a low complexity method and the orthogonal training symbols can be applied to the OFDMA case but CTP is not an ideal method for OFDMA.

Here, improved TDLS and FDLS methods named Separate Training Pilots (STP)-TDLS and STP-FDLS are introduced.

In [1,2], substantial benefits in terms of BER performance are demonstrated by use of Dynamic Sub-Carrier (DSA) algorithms in combination with MIMO-OFDMA. In practice, such a system relies upon the knowledge of CSI at both the transmitter (for use in DSA) and the receiver (for channel equalisation and decoding). In order to evaluate the effects of imperfect channel estimation, 4 cases are considered: ideal CSI in both DSA and channel, non-ideal CSI in DSA; ideal CSI in channel equalisation, ideal CSI in DSA; non-ideal CSI in channel equalisation and non-ideal CSI in both DSA and channel equalisation.

## II. SYSTEM MODEL

The OFDMA system considered here consists one Base Station (BS) and multiple Mobile Stations (MSs) all of which possess two antennas. The downlink is considered for the sake of simplicity. However, results are equally applicable to the uplink. The BS is considered to communicate simultaneously with multiple MSs, each of which is allocated a single sub-channel consisting of a given number of OFDMA sub-carriers.

The BS takes the downlink data for all MSs and applies independent bit level error control coding, symbol mapping and serial to parallel conversion. Each user signal is subject to either Space-Time Block Coding (STBC) or Spatial Multiplexing (SM). STBC is applied by Alamouti scheme [11,13]. SM in this paper is the simplest LST architecture – V-BLAST[12], in which data is simply de-multiplexed into 2 symbol streams for 2 transmit antennas. The resultant 2 coded/multiplexed user symbol streams with repeated preamble pilots are assigned to appropriate sub-carriers as indicated by the DSA algorithm which relies on channel state information (CSI) from a preceding channel estimation process. Subsequently, the symbols are OFDM-modulated via Inverse Fast Fourier Transform (IFFT) and a Guard Interval (GI), assumed here to be of sufficient length to prevent Inter-Symbol Interference (ISI), is inserted.

The signal received by the MSs takes the form of the BS signal, convolved with the channel transfer function matrix and additionally subject to AWGN. Symbols sent by the BS to other MSs (users) may be discarded after the FFT in the MS receiver. After extracting the GI and applying a Fast Fourier Transform process at each MS receiver, the sub-carriers assigned to a given MSs sub-channel are extracted according to the allocation of sub-carriers determined by the DSA algorithm. CSI can be achieved by channel estimation based on training pilots, which will be used for channel equalisation. Then, for an STBC system, a combining scheme [13] (proposed by Alamouti) is applied. In the SM case, a minimum mean-squared error (MMSE) receiver is used to balance multi-Stream Interference (MSI) mitigation with noise enhancement and minimize the total error [14].

Finally, the signals by zero-forcing process (in the case of SISO) or the combined (STBC) or demultiplexed (by MMSE in SM) signals are subject to Forward Error Correction (FEC). In this paper, convolutional encoding, CSI-enhanced soft Viterbi decoding and block interleaving are assumed as a standard case.

The whole process is shown in Fig.1.

## III. ‘DSA’ ALGORITHM IN MIMO-OFDMA

The DSA algorithm [1] for SISO system is validated to be low complexity and near optimal in [7] (10dB gain relative to random allocation OFDMA) and suitable to be applied in MIMO cases. The algorithm uses channel gain magnitude as a metric for sub-carrier allocation and aims to exploit multi-user diversity, ensure a fair allocation for all users and get maximum total perceived channel gain. In [2], 5 schemes are proposed to enhance the algorithm in [1] for MIMO-OFDMA. ‘Scheme 1’ was shown to offer the best performance in the un-correlated MIMO channels which are considered in this paper (other schemes are superior in combating the debilitating effects of channel correlation). Thus, this paper focuses on this variant of the algorithm exclusively. The performance of ‘scheme 1’ in un-correlated scenarios with STBC and SM is given in Fig. 2 which show gains of 6.5dB and 8dB at BER of  $10^{-3}$  respectively. However, such good results are achieved given the assumption ideal channel knowledge for both DSA and channel equalisation. The effect of non-ideal channel estimation is a crucial subject for this system. The algorithm of ‘scheme 1’ is not detailed again here because of space limitation, but it can be referred to [1] and [2].

## IV. CHANNEL ESTIMATION IN MIMO-OFDMA SYSTEMS

### A. Conventional ‘CTP’ channel estimation for MIMO-OFDMA

The knowledge of CSI is crucial for channel equalisation and decoding (at the receiver) in OFDMA systems. There are different ways to obtain CSI [11]. One is to use multiple OFDM symbols consisting of pilot symbols as a preamble for each user. In this paper, two consecutive pilot symbols are applied. Considering the lower bound of Mean Square Error (MSE) in LS estimator, pilots should be the set of Orthogonal Space-Time Pilot Matrices (OSTPM) [12]. The orthogonality should be obtained jointly in space and time domain. A Hadamard matrix is used to achieve such orthogonality:

$$X = \begin{bmatrix} x_{1,k} & x_{1,k} \\ x_{1,k} & -x_{1,k} \end{bmatrix} \quad (1)$$

where  $x_{1,k}$  is the transmitted pilot signals at a given sub-carrier  $k$ .  $X$  is the matrix of size of  $M \times T$  ( $M$  is the number of transmit antenna, equal to 2 in this case;  $T$  is the symbol period, for 2X2 STBC,  $T=2$ )

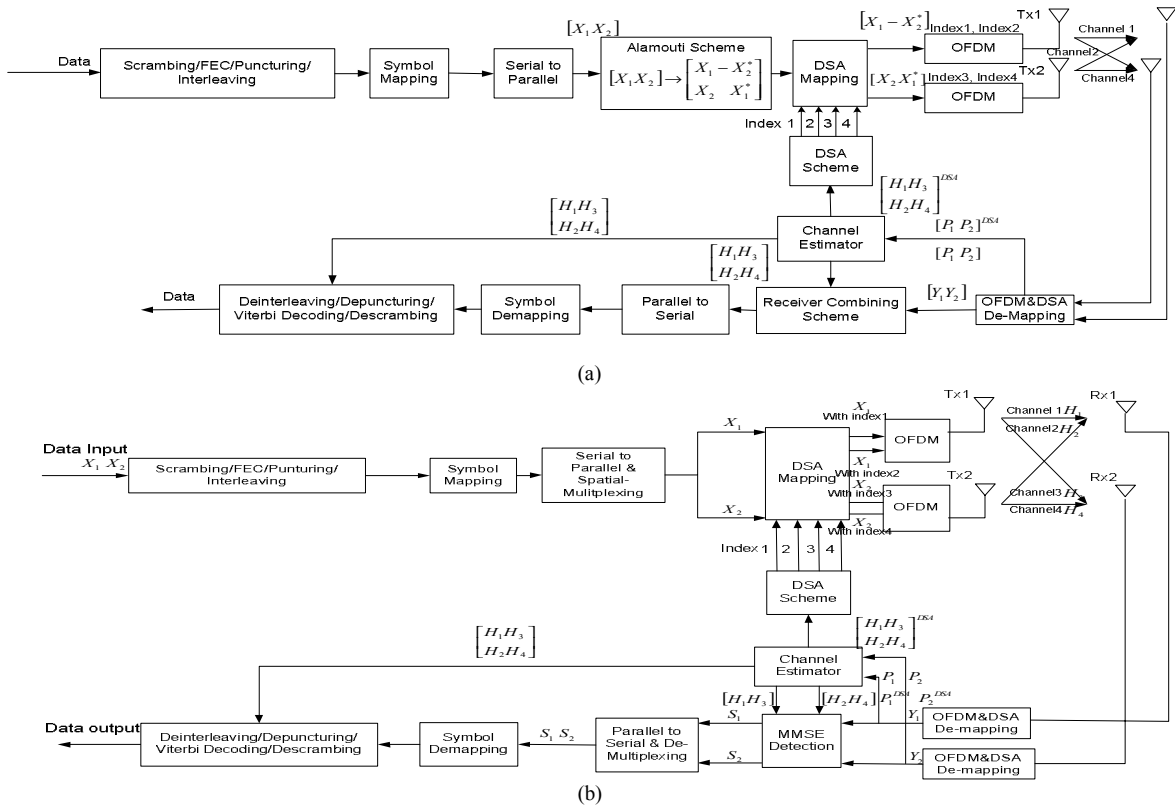


Figure 1. (a) STBC OFDMA System Model (b) SM OFDMA System Model

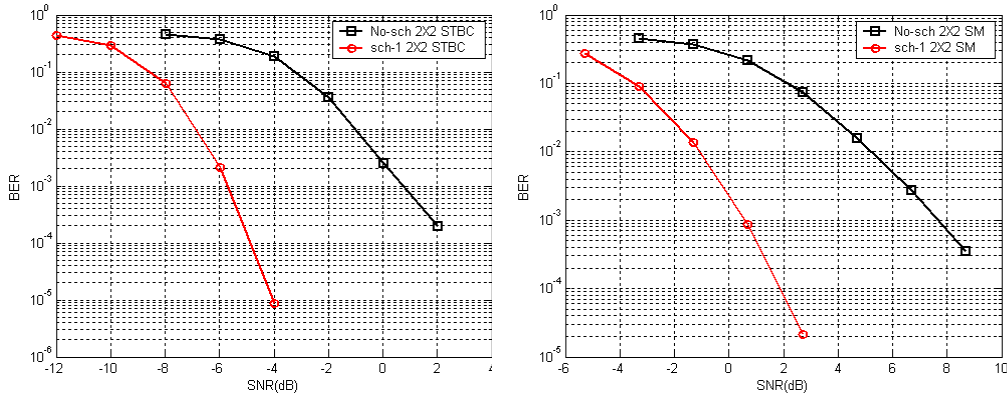


Figure 2 DSA 'scheme 1' with ideal CSI in un-correlated scenarios. Left: STBC, right SM

Such a matrix can help the receiver to separate the channels by linear combination of received signals  $R_{1,k}$  and  $R_{2,k}$  in the frequency domain so that the channel estimation can be decomposed in  $M$  single-antenna channel estimations for each receive antenna. This method is named Combining Training Pilot ('CTP') channel estimation. For example, in the frequency domain at receiver antenna 1:

$$\begin{aligned} R_{1,k} &= X_{1,k} H_{1,k} + X_{1,k} H_{2,k} + N_{1,k} \\ R_{2,k} &= X_{1,k} H_{1,k} - X_{1,k} H_{2,k} + N_{1,k} \end{aligned} \quad (2)$$

$$\begin{aligned} Y_{1,k} &= R_{1,k} + R_{2,k} = 2X_{1,k} H_{1,k} + N_{1,k} + N_{2,k} \\ Y_{2,k} &= R_{1,k} - R_{2,k} = 2X_{1,k} H_{2,k} + N_{1,k} - N_{2,k} \end{aligned} \quad (3)$$

Where  $R_{1,k}$ ,  $R_{2,k}$  are the received pilots;  $Y_{1,k}$ ,  $Y_{2,k}$  are the combination of receive signals;  $H_{1,k}$ ,  $H_{2,k}$  are frequency responses at a given subcarrier  $k$  of the channels between Tx1 and Rx1, Tx2 and Rx1 respectively;  $N_{1,k}$ ,  $N_{2,k}$  are AWGN. It is assumed that the channel responses are uncorrelated and constant during the period of the two OFDM symbols for a certain user.

From (3), the estimated channel gain matrix can be directly estimated in the frequency domain least square (FDLS) [8] – ‘CTP’-FDLS.

$$\begin{aligned} H_{1,k}^{FDLS} &= Y_{1,k} / 2X_{1,k} \\ H_{2,k}^{FDLS} &= Y_{2,k} / 2X_{1,k} \end{aligned} \quad (4)$$

In practice some virtual carriers at the edge of the band are used in MIMO-OFDMA systems. In this paper, considering a single user, there are just  $K=48$  sub-carriers used for transmission (see section V). Also, the channel impulse response can be assumed to have a number of coefficients not more than the guard interval length. Equation (3) can be rewritten for all sub-carriers by a truncated Fourier matrix  $F^{[K,G]}$ , in which only the rows corresponding to the observed sub-carriers and the first  $G$  columns are kept.

$$\begin{aligned} Y_1 &= 2X_1^{diag} F^{[K,G]} h_1^{[G]} + N_1 + N_2 \\ Y_2 &= 2X_1^{diag} F^{[K,G]} h_2^{[G]} + N_1 - N_2 \end{aligned} \quad (5)$$

where  $X_1^{diag} = \text{diag}\{X_{1,k}\}_{k=1:K}$ ,  $h_1^{[G]}$  and  $h_2^{[G]}$  are the time domain channel impulse response vectors.

The time domain least square (TDLS) channel estimator – ‘CTP’-TDLS, then can be given by [10]:

$$\begin{aligned} H_{1,TDLS} &= F^{[K,G]} [2X_1 F^{[K,G]}]^\dagger Y_1 \\ H_{2,TDLS} &= F^{[K,G]} [2X_1 F^{[K,G]}]^\dagger Y_2 \end{aligned} \quad (6)$$

If we denote  $A = [2X_1 F^{[K,G]}]$ ,  $A^\dagger$  represents the Moore-Penrose pseudo-inverse of the matrix  $A$ , i.e.  $A^\dagger = (A^H A)^{-1} A^H$  and  $A^H$  is conjugate transpose of  $A$ .

### B. Improved ‘STP’ channel estimation for MIMO-OFDMA

The combination approach mentioned above offers low complexity but the CSI will not be ideal since the pilot symbols themselves are corrupted by the Inter-carrier Interference (ICI) through the FFT and combining process. This method also cannot be applied to MIMO-OFDMA systems with sub-carrier allocations which differ between spatial sub-channels such as the DSA algorithm considered here.

However, in MIMO-OFDMA system, pilot symbols from different transmit antennas usually can be transmitted by different sets of sub-carriers for exploiting frequency and multiuser diversity, so that it is also easy to separate received pilot signals by detecting different frequency access, but not combining process. In this way, better CSI can be achieved with the same pilot power as considered in section A. This method is named Separate Training Pilot (‘STP’) channel estimation.

The STP-FDLS and STP-TDLS channel estimation in OFDMA system can be summarized as:

For FDLS, at receive antenna 1 and 2:

$$\begin{aligned} R_{1,1,k_1} &= X_{1,k_1} H_{1,1,k_1} + N_{1,1,k_1} & R_{1,1,k_3} &= X_{1,k_3} H_{1,2,k_3} + N_{1,1,k_3} \\ R_{1,2,k_1} &= X_{1,k_1} H_{1,1,k_1} + N_{1,2,k_1} & R_{1,2,k_3} &= X_{1,k_3} H_{1,2,k_3} + N_{1,2,k_3} \\ R_{2,1,k_2} &= X_{1,k_2} H_{2,1,k_2} + N_{2,1,k_2} & R_{2,1,k_4} &= X_{1,k_4} H_{2,2,k_4} + N_{2,1,k_4} \\ R_{2,2,k_2} &= -X_{1,k_2} H_{2,1,k_2} + N_{2,2,k_2} & R_{2,2,k_4} &= -X_{1,k_4} H_{2,2,k_4} + N_{2,2,k_4} \end{aligned} \quad (7)$$

where  $R_{m,t,k_p}$  is the received pilots from  $m^{th}$  transmit antenna at  $t^{th}$  symbol period and a certain sub-carrier set  $k_p$ ; left equation is for receive antenna 1 and right is for antenna 2.  $X_{m,k_p}$  is the transmitted pilot signals at a given sub-carrier  $k_p$ ;  $H_{m,n,k_p}$  is the channel gain between  $m^{th}$  transmit antenna to  $n^{th}$  receive antenna at a certain frequency  $k_p$ ;  $N_{m,n,k_p}$  is AWGN.

Thus,

$$\begin{aligned} H_{1,1,k_1} &= 1/2(R_{1,1,k_1} + R_{1,2,k_1}) / X_{1,k_1} \\ H_{2,1,k_2} &= 1/2(R_{2,1,k_2} - R_{2,2,k_2}) / X_{1,k_2} \\ H_{1,2,k_3} &= 1/2(R_{1,2,k_3} + R_{1,1,k_3}) / X_{1,k_3} \\ H_{2,2,k_4} &= 1/2(R_{2,2,k_4} - R_{2,1,k_4}) / X_{1,k_4} \end{aligned} \quad (8)$$

For TDLS:

$$\begin{aligned} R_{1,1} &= X_1^{diag} F^{[K_1,G]} h_{1,1}^{[G]} + N_{1,1} & R_{1,1} &= X_1^{diag} F^{[K_1,G]} h_{1,1}^{[G]} + N_{1,1} \\ R_{1,2} &= X_1^{diag} F^{[K_1,G]} h_{1,1}^{[G]} + N_{1,2} & R_{1,2} &= X_1^{diag} F^{[K_1,G]} h_{1,1}^{[G]} + N_{1,2} \\ R_{2,1} &= X_1^{diag} F^{[K_2,G]} h_{2,1}^{[G]} + N_{2,1} & R_{2,1} &= X_1^{diag} F^{[K_2,G]} h_{2,1}^{[G]} + N_{2,1} \\ R_{2,2} &= -X_1^{diag} F^{[K_2,G]} h_{2,1}^{[G]} + N_{2,2} & R_{2,2} &= -X_1^{diag} F^{[K_2,G]} h_{2,1}^{[G]} + N_{2,2} \end{aligned} \quad (9)$$

where  $R_{m,t}$  is the received pilots matrix for all certain sub-carriers.  $F^{[K_p,G]}$  is a truncated Fourier matrix for the whole set of sub-carriers for each channel.

Then the channel estimation can be achieved in a similar way in equation (6) for TDLS with  $R_{m,t}$  instead of  $Y_t$ .

These channel estimators processing separate training pilots for each transmit antenna can be applied into the MIMO-OFDMA system with different sub-carrier allocation for each spatial sub-channel in order to exploit more frequency and multiuser diversity without loss of channel knowledge.

The performance of STP and CTP methods are compared in section VI.

### C. Channel Estimation for MIMO-OFDMA with DSA algorithm

As well as in channel equalisation, the knowledge of CSI is very important to DSA for computing metrics and allocating sub-carriers. The effect of non-ideal CSI on DSA may not be the same as on channel equalisation because only the magnitude of channel gain is used as the metric in the DSA process. Hence the effect of non-ideal CSI on DSA and channel equalisation must first be investigated separately before the combined effect is considered. Also, the estimated CSI for DSA may be different to

that for channel equalisation in practice. There are 4 cases considered for evaluation of channel estimation in MIMO OFDMA:

- 1) Ideal CSI in DSA & channel equalization
- 2) Non-ideal CSI (STP-TDLS channel estimation) in DSA, Ideal CSI in channel equalization
- 3) Ideal CSI in DSA, Non-ideal CSI (STP-TDLS channel estimation) in channel equalization
- 4) Non-ideal CSI (STP-TDLS channel estimation) in DSA & channel equalization

## V. SIMULATION ENVIRONMENT AND PARAMETERS

In this paper, the simulation considers QPSK modulated, rate-1/2 coded, COFDM operating with a bandwidth of 100MHz as a candidate 4G physical layer as previously considered in [1]. The independent (un-correlated) quasi-static channels are modelled with 250ns RMS delay spread and 1760ns Excess delay with tap spacing of 10ns (a normalized RMS delay spread of 25, demonstrating that the system perceives a channel which is very much wideband). The guard time is fixed equal to the excess delay to ensure that the results are not affected by ISI.

The use of both Space-Time Codes (STBC) and Spatial Multiplexing (SM) is considered. 2000 independent identically distributed (iid) random quasi-static channels samples are used in simulations and the sub-carrier allocations updated via the DSA scheme for each such sample. In cases 2 and 4 of IV-C, the channel information for the DSA mechanism is achieved by post-processing the independent channel estimation for all users and all subcarriers in a MIMO-OFDMA case without DSA. For OFDMA and DSA algorithms, 16 users are considered and there are 768 usable sub-carriers in all. There are 48 usable sub-carriers for each user. The details are shown in Table I and Table II.

TABLE I. MODULATION PARAMETERS FOR OFDMA

MIMO strategy	STBC	SM (2Tx)
Modulation	QPSK	QPSK
Coding Rate	1/2	1/2
Data bits per sub-carriers (48 sub-carriers)	48	96
Data bits per OFDM symbol (all channels)	768	1536
Total Bit Rate [Mbit/s]	64	128
Coded bits sub-channel (48 sub-carriers)	96	192

TABLE II. CHANNEL MODEL

RMS delay spread	250ns
Excess delay	1760ns
Characteristic	Wideband Rayleigh
Environment	NLOS

## VI. RESULTS

The performance of combinations of STP and CTP FDLS and TDLS strategies are shown in Fig. 3 and Fig. 4 for STBC and SM cases respectively (with performance with ideal CSI shown as a reference) in random allocation ‘conventional’ MIMO-OFDMA system (without any DSA algorithm). It can be observed that STP-TDLS achieves the best performance. At BER of  $10^{-3}$ , there is only 1.2 dB degradation from the ideal case for STBC and 1dB for SM. For the case of CTP-TDLS, the degradation is 2 dB for STBC and 2.2 dB for SM. The cases of FDLS get the worse performance; degradation is: 2.3dB (STP) and 2.2dB (CTP) for STBC case; 4.2dB (STP) and 4dB (CTP) for SM.

The results for each of the cases discussed in section IV-C 1),2),3) and 4) are shown in Fig. 5 and Fig. 6 for STBC and SM respectively. It can be seen that the effect of non-ideal CSI in channel equalization (case 3) is 2.5dB degradation from ideal for STBC and 2.4dB for SM at BER of  $10^{-3}$ . The results for case 2) show a lower degradation, only 1.5dB for STBC and 0.6dB for SM. This shows that DSA is less sensitive to CSI error than CE. This can be justified by considering the process of DSA [1,2]; the allocation is made on the basis of a ranked channel gain, not the exact value of channel gain. The metric of sub-carrier allocation is only the magnitude of channel gain – phase is not considered.

For case 4, the impact of CSI error might be expected to be the sum of the effects in cases 2 and 3. For STBC and SM cases, the results show that – as expected – the degradation in performance from the ideal case is approximately the linear sum of the degradation for cases 2 and 3 (about 4dB in STBC case and 3dB in SM case).

Based on these evaluation results, channel estimation in MIMO-OFDMA systems with DSA can be investigated further (with specific focus on the use of STP-TDLS).

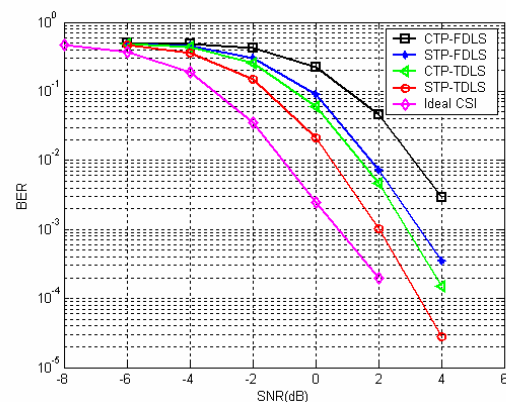


Figure 3. 2X2 STBC MIMO-OFDMA without DSA, with Channel Estimation



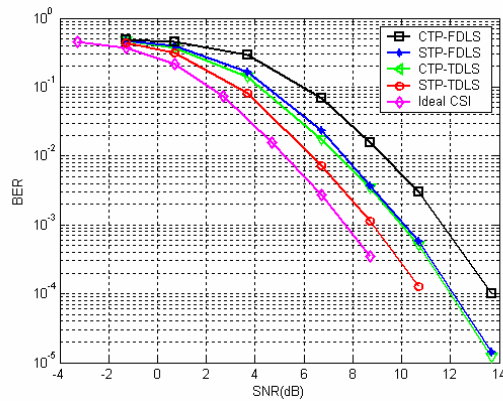


Figure 4. 2X2 SM MIMO-OFDMA without DSA with channel estimation

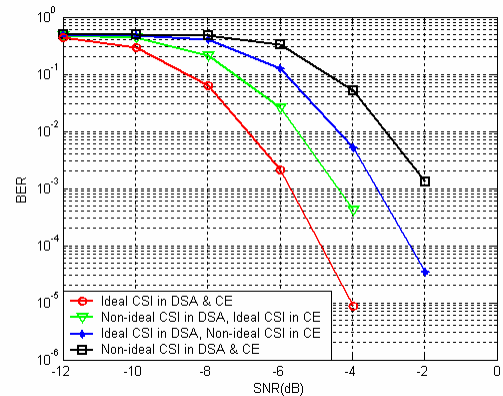


Figure 5. 2X2 STBC DSA OFDMA with channel estimation

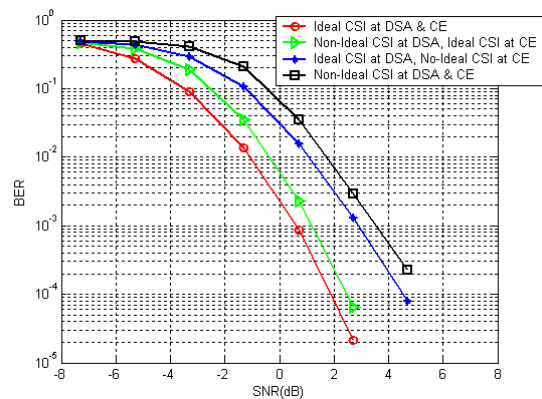


Figure 6. 2X2 SM DSA OFDMA with channel estimation

## VII. CONCLUSIONS

In this paper, the impact of channel estimation in MIMO-OFDMA systems (both without and with DSA) has been evaluated and analyzed. STP-TDLS offers the best performance in all cases considered including conventional CTP-TDLS and FDLS cases in OFDMA systems.

All the approaches considered here keep the low complexity of channel estimation and power of pilots as in conventional

OFDM. However when the number of transmit antennas increases, more training pilots may be required so that the efficiency will be reduced.

For systems with DSA, it is shown that DSA is less sensitive to the effects of CSI errors than channel equalisation. The total impact of CSI error is approximately the sum of its effect on DSA and channel equalisation separately. Considering the substantial gains achieved by DSA and its relative insensitivity to the effects of non-ideal channel estimation, it would appear a highly promising technique, even when taking account of the more realistic scenario of non-deal CSI.

## ACKNOWLEDGMENT

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